

From Nuclear To Sub-Hadronic Physics : A Global View Of Indian Efforts

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Abstract

A panoramic view seeks to trace the principal ideas governing the phenomenal growth of Nuclear Physics from a modest beginning in the Thirties, to an all-embracing field now protruding to the subhadronic on the one hand, and to high temperature QGP physics on the other. In this narrative, which makes no claims to completeness, Indian efforts have been highlighted vis-a-vis other similar efforts, within a common standard of global recognition.

1 Birth Of Nuclear And Particle Physics

Although Nuclear Physics was born more than a century ago, with the discovery of Radioactivity (A.H. Becquerel 1894) , its modern avatar dates back to 1932 , with the discovery of the **Neutron** by J. Chadwick. It was then that the *proton – neutron* composition of the *nucleus* became known for the first time. The next landmark event was the discovery by Hideki Yukawa (1935) of the short-range forces (the *meson*) that hold the nuclear particles (*nucleons*) together by very short-range forces, so as to account for Rutherford’s observation on the tiny size of the nucleus compared to its electronic jacket. The relative size problem was aptly summarized by Hans Bethe’s pin-head analogy. Namely, the nuclear size bears roughly the same ratio to the atomic size as does a pin-head to a standard sized living room. Further, the atomic size itself bears roughly the

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same ratio to the size of the pin-head ! However, Yukawa's candidate for the short-range forces was not immediately available, but only a "wrong" candidate in Carl Anderson's discovery (1937) of the *muon*(μ) which interacted weakly with matter, but which was later to revolutionize our concept of weak interactions (see below). The real breakthrough occurred only a decade later, with the discovery by Cecil Powell (1948) of the π -meson (*pion*) which showed the right property of "Strong Interactions" as envisaged by Yukawa. This formally marked the birth of *Particle* Physics, but in retrospect, the dynamic role of the *pion* as the mediator of strong interactions within the framework of modern Quantum Field Theory (*QFT*), was to come in perspective much later (see below).

2 From Nuclei To Quarks : An Overview

Since the thirties, the initial growth of nuclear physics had been rapid, in terms of both experimental and theoretical ideas. Experimentally, several classes of accelerators (Cockcroft and Walton, Van de Graeff and Cyclotron, as well as their numerous updates) were invented in quick succession as sources of energetic particles for the study of nuclear reactions in the laboratory, together with techniques for the detection of the reaction products (counters, cloud chambers, etc). The early work on nuclear reactions quickly established the short range character of nuclear forces and the small size of the nucleus. On the other hand, the electron spectrum of beta-decay was to open up still another front in unravelling the mysteries of short-range nuclear interactions, this time at the level of *weak* interactions ! First, it led to Pauli's ansatz of the *neutrino*(ν_e) as a *new* massless and electrically neutral particle, to account for the observed characteristics of the β -spectrum. This in turn led to Fermi's formulation of the *correct* theory of beta-decay, one in which the electron and its associated neutrino (ν_e) were to play the role of a fundamental pair (e, ν_e) forming a *weak* interaction current ! A second pair (μ, ν_μ) was to come.

In the meantime theoretical efforts had been under way since the mid-Thirties (at the hands of Wigner, Bethe, Heisenberg, Pauli, Peierls, and others) at organizing some principal features of nuclear interactions, in terms of certain general principles of Symmetry and identity among the nuclear constituents. Thus while Pauli's neutrino hypothesis paved the way to an understanding of *weak* interactions, Heisenberg's contribution consisted in

recognizing the key role of *exchange* forces in the two-nucleon interaction, which is rather simply realized by the *charged* nature of the pionic force. Bartlett in turn proposed another variant, viz., the *spin*-dependence of the two-nucleon force. These individual features were subsumed in the all-embracing idea of Wigner on the role of *Symmetry* via Group structures which provided a real breakthrough into the nature of *strong* interactions. This symmetry manifested as a rotational invariance of the nuclear force within the space of $SU(4)$ which encompasses two $SU(2)$ subspaces representing *spin* and *isospin* respectively. This important principle was to form the bedrock of all subsequent microscopic theories of nuclear forces.

In a major development two decades after the Fermi theory of beta-decay, the Lee-Yang theory of parity violation in beta-decay was quickly confirmed by the experiment of C.S.Wu, eventually giving rise to a new theory of weak interactions with emphasis on *handedness*, rather than parity, as the conserved quantity (cent per cent violation of parity !). In the jargon of Particle Physics, this was called "*CP*" conservation, where "*C*" and "*P*" stand for charge conjugation (particle-antiparticle interchange) and parity (left-right) reversal, respectively. The foundations of this new theory, although originally suggested by Hermann Weyl in 1929, were laid in a fresh light by Sudarshan-Marshak, Feynman-Gell-Mann, and Landau-Salam. The Weyl theory which was thus vindicated after initial rejection (on grounds of "sanctity" of parity conservation), brought to the fore the traditional conflict of opposites in Physics, this time as a fight between Truth and Beauty [S. Chandrasekhar, Physics Today 1969], when the latter eventually won, although not at the cost of the former. And in this extended framework of Physics, the (hitherto unwanted) Anderson *muon*, together with its neutrino partner ν_μ , found a natural place in parallel with the (e, ν_e) pair, eventually leading to the modern theory of weak interactions now known as the Glashow-Salam-Weinberg model. [For a perspective on the early phases of the weak interaction sector, see P.K. Kabir, "The CP Puzzle: Strange Decays of K^0 ", Academic Press London 1968].

2.1 The Pion as the Trigger of Nucleon Resonances

As the harbinger of strong interactions on the other hand, the *pion* turned out to be the king-pin controlling the evolution of nuclear physics. While its theoretical status in the

nuclear domain as a key element in strong interaction physics has been ever on the rise, its immediate role as an *experimental* probe into the nuclear interior was almost instantly realized by the classic experiments (in early 50's) of H.L. Anderson and his team at the U. of Chicago accelerator, shooting pion beams at hydrogen-like targets. The immediate fall-out was dramatic : the existence of short-lived peaks, termed *resonances*, soon to break up into their original constituents, nucleons and pions, subsequently to be called *hadrons*, together with their "strange" partners (see below). The first and most prominent peak was the so-called "33" resonance, or Δ , about 300 MeV above the nucleon, to be followed by several others in fairly quick succession, so that the energy field above the nucleon was soon to be strewn with many nucleon-like but short-lived peaks ! And as the energy of the incoming pion beam increased, several more meson-like states (ρ , ω , ϕ) also could be identified via more elaborate analysis. Indeed in a rather short time span, (less than a decade since the start of the Chicago experiments), the entire nucleon-meson (*hadron*) scenario was dotted with short-lived states spanning energies up to a *GeV*, (i.e., almost the nucleon energy), above the nucleon's. To add to the chaos, still another nucleon-like species (Λ) and a corresponding pion-like meson (*Kaon*) were added to the original nucleon-pion club, as a gift from Cosmic Ray studies. And soon their corresponding higher lying short-lived states were to be manufactured by higher energy beams in the laboratory, leading to an increase in Wigner's group classification from $SU(4)$ to $SU(6)$ "hadrons".

The question then arose: Should these short-lived peaks qualify as elementary particles on par with nucleons and pions ? Considering the fact that they were found to be highly unstable, breaking up into their stable, lower energy species, they looked more like what atomic excited states were to their ground state counterparts. As if to strengthen this view, the seminal electron scattering experiments on hydrogen targets by Hoffstadter et al (1957-) at the Stanford Linear Accelerator, showed clear structure effects usually associated with *composite* bodies, in the hitherto believed 'elementary' protons and neutrons whose experimental signatures showed up as their "charge" and "magnetic" form factors. And now their *strange* (Λ and *K*-like) counterparts led to the extended concepts of "strange baryons and mesons " under the generic name of *hadrons*. The situation now was strongly reminiscent of the pre-Bohr stage of the atom, this time at the sub-nuclear

level, suggesting a third generation of elementarity.

2.2 Third Generation of Elementarity: Quarks

At this stage it made more sense to think of substructures of *hadrons* than to give them elementary particle status ! It was at this time that the *quark – model* of Gell-Mann (1964) and Zweig (1963) was born, with curious properties of invisibility and fractional charges. The quark-model, which has never looked back since then, has now grown into a non-abelian ”gauge” theory of the Yang-Mills type with a multicomponent attribute called ”Color” , under the name of Quantum Chromodynamics, QCD for short, on similar lines to the single attribute (charge) gauge theory known as QED, with quarks and gluons taking the place of electrons and photons respectively. QCD however has properties complementary to QED, namely, while the interaction strength of QED decreases with increasing distance, that of QCD increases with increasing distance, a property which goes under the name of *confinement* ! The opposite is true for decreasing distance. In particular, the QCD coupling strength *decreases* with decreasing distance, a property that goes by the name of *asymptotic freedom*. This unique property of QCD as a non-abelian theory was first shown by Gross-Wilczek and Politzer (1973) and has been so well confirmed by experiment, that these 3 authors were honoured by the Nobel Prize for 2004 ! [Fuller details are given in the Article by Rajasekharan on the developments in Particle Physics].

It was therefore inevitable that such fundamental substructures as quarks and gluons should penetrate deep into the domain of Nuclear Physics, and carve out a new sector, ”hadron physics”, as a subdiscipline of the latter. In this respect, the demarcation between Nuclear and Particle Physics, which has never been sharp, has been continually shifting ground, with the traditional nuclear range ($1 - 100\text{MeV}$) slowly extending to the few GeV regime and even beyond, while the particle physics range is continuously yielding place to the former by shifting further and further to the right in tandem ! [This trend is best reflected in the shifting PACS Classification Scheme over the years].

3 Growth Of Nuclear Physics: 3 Sectors

The growth of NP against this huge background has necessarily been multidimensional, since the subject touches several distinct sectors from atomic to hadronic, involving their mutual interactions from strong to electroweak. And of course each sector has generated its own techniques (both theory and experiment), all within the general head that has come to characterize NP. To get an idea of the complexity of NP w.r.t. its atomic counterpart, the biggest difference comes from a lack of quantitative knowledge of the precise nature of the former, vis-a-vis the latter (whose structure is better understood). Indeed, the biggest stumbling block on the progress on the strong interaction front had for long been the tentative status of the two-nucleon interaction throughout the Fifties, leading M.L. Goldberger (considered an authority on nuclear theory) to make a typically Churchillian remark: "in no other field has so much effort been wasted towards so little effect". As if to overcome this obstacle, Hans Bethe invoked the *Second Principle* theory according to which the $N - N$ interaction was to be taken as the basic starting point for formulating the applications to nuclear physics problems (see further below).

It is such broad principles as above that have characterized the phenomenal growth of NP over the last 5 decades, necessarily in tandem with its related fields from atomic to sub-hadronic. For a rough classification, the principal divisions are : A) "classical" Nuclear Physics; B) Pion-Nuclear Physics and Quark Model; C) Nuclear Astrophysics and QGP transitions. Each division (with further subdivisions) has had a liberal sprinkling of further principles or "Models" at different levels of theory. The scope of this narrative is however limited: the emphasis is mainly on those areas where *Indian* contributions (working inside and outside the country) have been globally visible during the last half century.

4 "Classical" Nuclear Physics : Shell Model

Nuclear Physics came of age after a major break-through which occurred with the landmark discovery by Maria G Mayer and Hans D. Jensen (1949) of the *Spin - orbit* force in the nuclear shell structure with an *opposite* sign to that obtaining in the atomic shell structure. This result, which had a firm basis in Wigner's great idea of Symmetry in

nuclear forces, gave a concrete shape to the *nuclear shell model*, (despite the high density of a nucleus), albeit with an *inverted* order w.r.t. the atomic shell structure, and provided a natural understanding of several properties of nuclei, far beyond the "magic numbers". In particular, some general results emerged, using the symmetry between "particle" and "hole" states in the shell model, which was christened as the Pandya Theorem by J.B. French of Rochester, as outlined below.

4.1 Applications of the Shell Model: Pandya Theorem

The Nuclear Shell Model proved a strong impetus for more concrete formulations of Angular Momentum Theory (Elliot and Skyrme, 1951-52) greatly extending Racah's pioneering work. An important feature of such formulations was that "particle" and "hole" configurations play closely analogous roles. This is still another aspect of "Symmetry" at the nuclear level which closely resembles the more familiar concept of particle-antiparticle symmetry, dating back to Dirac's hole theory for the electron field. To see the analogy more closely, let us recall that the 'vacuum' in the electron's field corresponds to the state in which all negative energy states are filled. And if enough energy (more than $2mc^2$) is pumped into this state, one of the negative energy electrons jumps into a positive energy state, creating a 'hole' in the vacuum; then the new state looks like an (excited) electron-positron (particle-hole) configuration. Analogously in a nucleus, the 'vacuum' state is the 'ground' state in which all the 'shells' are filled; this condition is just met in the so-called "magic nuclei". But if enough energy is pumped into such a nucleus, so that one of the nuclear particles (a nucleon) is raised into a higher shell, then one has an (excited) particle-hole configuration, just like in the electron case ! And just as the electron-electron symmetry in the former case has its counterpart in the electron-positron symmetry, similarly the nucleon-nucleon symmetry in the nuclear case has its counterpart in the nucleon-hole symmetry. As a word of caution, however, the analogy must not be carried too far : For while in the electron field case, the 'hole' (positron) is a genuine *antiparticle* (positron), the 'hole' in the nucleon configuration is *not* a true antinucleon, and behaves like one only for the limited purpose of 'going in and out of closed shells'. [the energy scales involved are in the *MeV* vs *GeV* ranges respectively]. Even within this limited applicability, the particle-hole concept in nuclear physics holds out strong

correlative powers as we shall see below.

From an applicational point of view, the situation in the mid-fifties was that shell-model calculations for nuclear energy levels were possible only for a few *active* nucleons in the configuration space of as many active orbits. These were called the ‘major shells’ of which the primary ones of physical interest were $s - d$ and $f - p$. For such calculations, the primary input was a two-particle matrix element of the form

$$\langle j_1 j_2 J | H | j'_1 j'_2 J \rangle,$$

in the notation of a jj configuration. Thus many calculations were made at the beginning of a major shell ($s - d$ or $f - p$). In this context, Gulio Racah had established a sort of *symmetry* between *particles* and *holes* in a shell. This important symmetry could thus be exploited to provide a connection between two-particle and two-hole configurations so that results for the former would be automatically applicable to the latter types.

Now came the question of a possible connection between a 2-particle configuration and one with 1-particle plus 1-hole. This important question was asked (and answered) by a young Indian physicist Sudhir Pandya working with J.B. French at Rochester. Using an extension of the symmetry argument of Racah, he showed that indeed the matrix elements of 2-particle and 1-particle plus 1-hole configurations are related by an equation of the form

$$\langle j_1 j_2^{-1} J | V | j_1 j_2^{-1} J \rangle = \sum_x (2x + 1) W(j_1 j_2 j_1 j_2 J x) \langle j_1 j_2 x | V | j_1 j_2 x \rangle$$

connected by Racah coefficients. Pandya applied this result to the lowest four levels of ^{38}Cl and ^{40}K where only a few spin-parity assignments had been made. This gave rise to concrete predictions which were testable. J.B. French (who called it the *PandyaTheorem*), got the Utrecht nuclear physics group to verify this result to within 10KeV ! This was a most impressive confirmation, considering the fact that the usual limits of agreement with experiment were taken as the order of 100KeV , because of the uncertainties of nuclear matrix elements which are in the MeV regime. More significantly, this confirmation also suggested that the states involved were almost pure $d_{3/2}f_{7/2}$ and $d_{3/2}f_{7/2}^{-1}$ states ! Further, by assuming the wave function to be “pure” (no configuration mixing), one could set an upper bound to the contributions of 3-body forces to the energies of nuclear states ! Indeed the Pandya result was the first reliable and quantitative estimate of 3-body

forces within the framework of the shell model. It also provided a very useful tool for extending shell model calculations across shells, for systems involving *both* particles and holes. Indeed when giant resonances were discovered and described in terms of collective particle-hole excitations, the value of this result was quickly realized.

4.2 Collective Excitations, Pairing Correlations

The Pandya theorem is a good illustration of the richness of information forthcoming from a judicious use of subtle symmetry principles connecting vastly different sectors of nuclear systems. Another early discovery in nuclear structure was the large quadrupole deformation of certain classes of nuclei, leading to the emergence of new, *collective*, degrees of freedom (Bohr–Mottelson). These were basically collective excitations (rotations, vibrations) of non-spherical nuclei, leading to a greatly simplified description of the energy levels of *deformed* nuclei, albeit in a highly "macroscopic" form. To give a more *microscopic* description of these ideas, was a big challenge that was to extend over a few decades involving a synthesis of the collective and nuclear shell models. This effort has had a long history, one in which the concept of *pairing* (correlations between nucleons coupled to "zero spin") proved crucial, as it led to a simple understanding of the energy gap between even-even and odd-odd nuclei, in close analogy to the BCS Theory of Superconductivity in the totally different area of condensed matter physics. Later, the pairing idea got a major boost in the form of the "Interacting Boson Model (IBM)" (Arima–Iachello, 1974), in which the d.o.f.'s are those of effective zero spin *bosons* made up of two nucleons of opposite spins. This boson-like character in turn proved mathematically equivalent to *paired* fermion-like states, through a suitable mapping process of both "unitary" and "non-unitary" types. These ideas have been extensively developed on a global scale, with a view to a more concrete synthesis of the (macroscopic) collective model with the (microscopic) single-particle shell model. In this respect, Indian participation has been significant, with Y. K. Gambhir having established a one-one correspondence between the Shell Model states and the second quantized version of the basis states in the Quasi-particle theory.

4.3 Nuclear Reactions : Direct Interaction Theory

In parallel with these breakthroughs in nuclear structure, there had been equally impressive progress in the dual sector of nuclear reactions, whose understanding could be classified in terms of i) a two-step process: resonance formation and decay independent of the formation mode; and ii) a one-step process: reaction time comparable to the passage of the projectile through the nuclear volume. The celebrated example of the first type is the Breit-Wigner one-level formula (subsequently generalized to more levels, like the Kapur-Pieirls formula), while the second type could be described by an effective "optical potential" with real and imaginary parts. Seminal work in the second category was carried out by (the late) Manoj Banerjee and Carl Levinson who developed the Direct Interaction theory of inelastic scattering, using realistic shell-model states under $SU(3)$ classification, wherein a 'direct interaction' is postulated to take place anywhere inside the nuclear volume, with remarkable agreement with data (on carbon) over a wide energy range.

The '70's and '80's were a period of consolidation for a quantitative understanding of nuclear physics with improvement in experimental techniques and a matching growth in computer technology to support the theoretical framework. New experimental techniques included the use of i) heavy ion beams to investigate new features in nuclei ; ii) electron beams for mapping precise nuclear-charge distributions (CEBAF) on the lines of Hofstadter's original experiments ; iii) new forms of accelerators using superconductivity; iv) intense pion and kaon beams under the name of "meson factories" to study specific features of nuclear properties in precise details; and v) K^- beams targetted at chosen nuclei, to produce a new class of nuclei, termed "hypernuclei", in which a long lived baryon (Λ) is bound with the conventional nucleons.

4.4 Microscopic Models And Nuclear Structure

The Bethe Second Principle Theory proved a strong incentive to the formulation of more microscopic models of nuclear structure in terms of the two-nucleon interaction taken as basic. This is best exemplified by the Bethe-Brueckner theory of infinite matter using systematic approximations like the Hartree approximation with simplified forms of the basic nucleon-nucleon forces which leads to the "mean field" in which nucleons move.

However even before the the full ramifications of the former, some limited but important issues like the understanding of spin-orbit forces in nuclei, in terms of the well-known 2-body tensor force as input, had engaged the attention of nuclear theorists. In particular, the magnitude of this tensor force was found inadequate for understanding the strength of the spin-orbit force governing the Shell-Model. This led Robert Marshak (with his student Signell) to propose a primary spin-orbit force (apart from the usual tensor force) to account for its role in nuclear structure. B.P. Nigam and M.K. Sundaresan (1958-59) showed that this ‘direct’ spin-orbit force could indeed account for the magnitude of the shell-model spin-orbit force. Other applications of a similar type such as the calculation of nuclear energy levels in terms of simplified two-body forces (Mittra-Pandya 1960), were generalized by Kramer-Moshinsky (1960) for the matrix elements of two-body forces in c.m. and relative coordinates, later to be known as Moshinsky Brackets.

4.4.1 Hugenholtz-VanHove (HVH) Theorem

For more substantial applications of microscopic methods, the Bethe-Brueckner theory had to face the rigours of the Hugenholtz-Van Hove (HVH) Theorem which deals with the single particle properties of an infinite interacting Fermi gas at absolute zero of temperature, and yields a relation amongst Fermi energy (E), the average energy (A) per particle and the pressure of the system. However for a saturating system at equilibrium, the pressure vanishes, and one gets a simple relation $E = A$, i.e., for an interacting Fermi system in the ground state, its average energy becomes equal to the Fermi energy ! This is a rare theorem in many-body physics which is rigorously true up to all order of perturbation. It is also remarkable that the theorem does not depend upon the precise nature of interaction, and is in general valid for any interacting self-bound infinite Fermi system, and in particular for nuclear matter. It was with this theorem that Hugenholtz and Van Hove found internal inconsistency in the early nuclear matter calculation of Brueckner (Phys. Rev. 110(1958)597). More dramatically, the HVH theorem did not spare even the celebrated Bethe-Weizsacker Mass formula which had been conceived in a ”classical” manner, as was first pointed out by Satpathy and Patra [Phys.Rev.Lett.51(1983) 1243], using a generalized HVH theorem for infinite nuclear matter in which a distinction was made between the numbers of protons as well as their respective fermi energies.

4.4.2 Extreme Nuclear States

The work of Satpathy et al, [Phy. Rep. 319(1999)85] had important ramifications on several new areas of NP , especially those nuclei which are involved near the limits of nuclear binding. According to the usual wisdom based on Wigner's symmetry energy considerations, for a fixed number of protons not more than a certain maximum number of neutrons can be bound, and vice versa for a fixed number of neutrons. These "drip lines" are of interest in the laboratory, since nuclear properties may change drastically near these. More especially, they are of interest in (high T) stellar processes where a sequence of captures takes place rapidly. Exploration of these limits is a comparatively recent phenomenon (since 1990's). One interesting phenomenon that occurs along the drip line is "proton radioactivity" where the nuclei are "dripping" protons since their binding energy is insufficient , but the Coulomb barrier retards their emission. Neutron excess nuclei are more difficult to reach in the laboratory; since neutrons see no Coulomb barrier, their density distributions extend far beyond 'normal' nuclear radii, indeed well beyond the corresponding proton distributions in neutron rich nuclei. This asymmetry in turn will cause a change in shell structure due to a substantial reduction in the spin-orbit term. For all such nuclei, the Satpathy et al work suggest the existence of *new magic numbers* and associated new islands of stability which have profound implications on the broadening of the stability peninsula.

4.4.3 Yrast states

Another kind of extreme nuclear states are the so-called Yrast states which are formed as follows : compound nuclear states at high excitation are first produced by medium energy (200MeV) projectiles of heavy nuclei like ^{48}Ca incident on targets like ^{120}Sn . These decay rapidly by emitting neutrons, leaving the product nucleus in a fast rotating state with large angular momentum. Now in a rotating frame, the excitation energy is not too high wrt the *lowest* energy that the nucleus can have at this angular momentum – the so-called *yrastline*– but under the influence of *centrifugal* forces, the lowest configuration in the nucleus can be quite different from those at low angular momentum. Stated differently, the shell structure of nuclei becomes distorted under the centrifugal effect of rotation, and new levels of relative stability may develop as functions of quadrupole deformation. As a

result, there appear new classes of nuclear states with high deformation, in which several nucleons have individual quantum numbers that differ from those of the normal ground state.

4.4.4 Bethe-Brueckner Theory in Practice

Despite the formal constraint of the HVH theorem, the Bethe-Brueckner theory proved a strong incentive to researchers in formulating new techniques for nuclear reactions and structure calculations within its framework. (The late) Manoj Banerjee in particular, with his student Binayok Dutta Roy, was one of the first to apply Brueckner's reaction matrix to a finite nucleus calculation. Other Indian contributions in this field are due to Nazakatullah (TIFR) and M.K. Pal (SINP).

4.4.5 Hartree-Fock techniques

Nuclear many body calculations within the Bethe-Brueckner framework were developed along two distinct tracks: Hartree-Fock and Thomas-Fermi. Significant Indian contributions in the former were made by Y.K. Gambhir, leading to deviations from the mean field approximation. Relativistic effects were also studied by Y.K. Gambhir and C.S. Warke on the basis of the J.D. Walecka formalism. Experimental techniques for detection of these micro-states include electron scattering as a convenient tool for measuring the individual shell-model orbitals as well as the corrections due to correlation effects arising from the short range N-N interaction. The V. Pandharipande group (1997) at the Univ of Illinois showed substantial deviations from a mean field approximation due to pair correlation effects in the high momentum regime, in agreement with observation [Rev Mod Phys. **69**, 981 (1997)].

4.4.6 Thomas-Fermi method

The Thomas-Fermi approximation in nuclei was developed by R.K. Bhaduri and C.K. Ross (Phys.Rev.Lett 27, 606 (1971)) in the form of a systematic expansion of higher order terms, termed the "Extended Thomas-Fermi (ETF) method" by the authors. The latter has been applied extensively in shell corrections (in fission) and in the construction of mass formulae.

4.5 Few–Body Systems

The Bethe Second Principle Theory, which has been central to microscopic formulations of the nuclear many-body problem, despite the constraints of the HVH Theorem, came in particularly useful for the (much smaller) "few-body" systems whose mandatory quantum mechanical formulation would automatically satisfy such constraints. Historically, the importance of such systems may be traced back to the traditional insolubility of the atomic helium 3-body problem which stemmed from the non-linearity inherent in the Coulomb interaction, a disease which was not cured by quantum modifications, but had to wait for another 70 years for the concept of 'periodic orbits' in classical non-linear systems to come to the rescue ! [See Introduction, Sect 3 for essential logic]. Of course, the traditional solution which has since held centre-stage in physics, was the the famous variational principle proposed by Hyllaraas to tackle that problem. The success of this principle therefore came in handy for the *nuclear* 3-body problem where the ground state energies of 3H and 3He were quite fashionable topics of research in the initial stages of NP. The stumbling block was however the use of variational wave functions which would hide the micro-causal structure of the 3-body wave function that cannot be obtained without solving the corresponding Schroedinger equation . For the atomic helium problem there was no choice, since the basic (Coulombic) structure of the two-electron force was not negotiable, but other options were available for the nuclear 2-body potential which was at best parametric, thanks to the Bethe Second Principle Theory. This option could now be turned to a practical advantage since the 'effective range theory' (valid at low energy) could fix only two constants—the scattering length and effective range, and many 'potentials' could be constructed with these two parameters in place. Y. Yamaguchi (1954) took advantage of this choice by using 'separable potentials' which would make the Schroedinger equation exactly soluble, and produce an "exact" wave function without variational uncertainties. Mitra [Nucl Phys 32, p529, 1962] and his colleagues (B.S. Bhakar 1963, V.S. Bhasin 1963, V.K. Gupta 1965) took this result a step further by proposing that a separable 2-nucleon potential would reduce the (insoluble) 3-body problem to an ordinary 2-body problem so that its microcausal structure would no longer be held hostage to variational uncertainties. In the initial days of computer technology, this was a big help for a physical understanding of the 3-body system via its rich structure,

whose information is effectively coded in the *off-shell* matrix elements of the 2-nucleon potential. The idea caught on rather quickly on a global scale, as an intensely practical way to handle the 3-body problem with its rich applicational field, at just the right time when Faddeev proposed his 3-body formalism, since the full-fledged structure of a 3-body wave function (with its crucial off-shell ramifications) was free from the uncertainties of variational wave functions. Gillespie-Mitra- Panchapakesan- Sugar (1964) soon extended the formalism to the 4-body problem, but the precise mathematical significance of the Yamaguchi separable potential became clear: the N -body nuclear problem with separable potentials gets exactly reduced to the level of an ordinary $(N - 1)$ -body problem ! With the rapid increase in computer technology, the ‘separable’ potential ansatz got generalized to separable expansions for arbitrary potentials, and the few-body problem soon got industrialized with bigger teams working on more realistic 2-body interactions involving both scattering and bound state problems.

4.5.1 Three-Body Forces

As an offshoot of the Bethe Second Principle Theory, the $N - N$ interaction soon acquired some allied concepts since this effective formulation was not microscopic enough for handling higher order effects, unlike, e.g., a standard Yukawa-type interaction mediated by a field. A popular concept in this regard arose under the name of ”Three-body forces”, wherein *three* nucleons are simultaneously involved in the interaction ! The concept can be formulated in several ways ranging from a purely empirical contact (δ -function) interaction, to elaborate diagrammatic forms involving two pion exchanges (in succession) among the 3 participating nucleons; [the latter necessarily involved the folding of the Yukawa-type pion- nucleon vertex]. Special care was needed to ensure that such diagrams are truly ”irreducible”, i.e., they are not part of the iterations of the input two-nucleon interactions. This in turn causes uncertainties in the precision of estimates which often vary. This field has generated much literature. prominent names being Bruce McKellar and R. Rajaraman, but is still largely open-ended.

5 Pion-Nuclear Physics & Quark Model

These areas represent the main off-shoots of "classical" NP, because of the growing importance of new emerging degrees of freedom symbolized by the *pion* on the one hand, and the *quark* on the other. Indeed the *QuarkModel* of the *hadron* (nucleon and meson) came as an 'answer to prayer' for the practitioners of traditional nuclear physics since it was almost tailor-made as a *few – body* scenario for these nuclear constituents at the *quark* level ! It may be recalled that the quark model had been evolving in *two* independent directions, viz., a) as primary *currents* obeying the laws of $SU(3) \times SU(3)$ algebra; and b) as *constituents* of hadrons in much the same way as *hadrons* are constituents of nuclei. [The $SU(3)$ is a reminder of the inclusion of strange (*s*) quarks in the same package as non-strange (*u, d*) $SU(2)$ quarks]. It is the constituent quark scenario (b) that almost fitted into the few-body scenario at the quark level, while the 'current' quark picture was more suited to the conventional language of currents for particle physics; [see Rajasekharan for the latter]. An intermediate approach was to formulate NP with a special status to the pion as an effectively 'elementary' particle interacting with nuclear constituents, while in the full-fledged constituent quark model all nuclear constituents are treated as quark composites.

5.1 Chiral Properties of the Pion

The *pion* as the smallest quark composite has found its special role as a *bridge* between hadron and quark-gluon physics. This role of the pion owes its origin partly to certain "exact" formulations which incorporate its solitonic properties (the Skyrmion) even before the birth of the quark-model. Secondly the insolubility of QCD led to certain alternative formulations incorporating at least some important properties of QCD, especially *chiralinvariance*. This means that the quark-gluon Lagrangian is invariant wrt chiral transformations in the limit of zero *ud* quark masses. By eliminating the quark and gluon d.o.f.'s from a path integral formulation of QCD in favour of pion-like fields having the Skyrmionic properties, Gasser and Leutwyler (1984) derived an effective Lagrangian in the form of a momentum expansion which was chirally invariant. This "chiral perturbation theory" which was thus rooted in QCD, was enormously successful in reproducing certain

known pre-QCD results (such as the σ model, as well as predicting correctly many low energy hadronic properties. And an extension of these ideas to include vector and axial vector mesons has proved equally fruitful. This area has been one of the favourite hunting grounds of applicational hadron physics, one in which Indian workers have played leading roles in association with their global counterparts. In particular, (the late) Manoj Banerjee was one of the pioneers in realizing the importance of chiral symmetry in hadronic structure, and doing concrete calculations in the chiral soliton framework. Other Indian workers who have made significant contributions in this field, together with their many western counterparts are Rajat Bhaduri, C.S. Warke, Y. K. Gambhir and V. Devanathan, among the more prominent ones. In particular, in the related field of muon-capture in nuclei, V. Devanathan and R. Parthasarathy have done significant work on recoil polarization and gamma-neutrino angular correlations in muon capture (1980-85) which motivated D. Measday's experiments at TRIUMF on muon capture by silicon-28, leading to more reliable estimates of the pseudoscalar coupling constant than obtainable from PCAC estimates. Subsequently, Parthasarathy made more detailed studies of neutral current induced neutrino excitations in Carbon-12 nuclei which formed the basis of the KARMEN experiment on neutrino oscillations.

5.2 Constituent Quarks, Statistics And All That

We now come to the constituent quark model which has been patterned closely after the corresponding formulations of nuclear physics in terms of nuclear constituents, albeit at the level of one and two nucleons in practice, and that too in terms of Bethe's Second Principle Theory, despite the existence of QCD as a formal strong interaction theory !

5.2.1 Quark Statistics

An important prerequisite of any formulation with constituent quarks is the statistics they are supposed to obey. By simple arguments, the apriori choice would naturally be Fermi statistics, taking the known number of d.o.f.s into account (spatial, spin and flavour). On the other hand there were both dynamical and observational constraints with this simple choice. "Dynamical" because the minimal fermionic state compatible with the (symmetric) 56 representation would be spatially *antisymmetric*, but this would go

contrary to standard dynamical expectations (Gursey-Kuo-Radicatti 1964) which would prefer the lowest (ground) state to be spatially symmetric. Observationally, a spatially antisymmetric ground state of 3 quarks should show *nodes* in the proton e.m. form factor at rather low momenta (Mitra-Majumdar 1966), something which is not observed. To overcome the dynamical problem of a symmetrical wave function, Greenberg (1964) suggested a new form of statistics termed *parastatistics* which would yield a symmetrical ground state as required. But such a hypothesis would go against the canonical Bose-Fermi alternatives, and was soon overshadowed by the now familiar d.o.f. termed *color* a la Gell-Mann, in addition to space-spin-flavour, so that Fermi statistics could be logically accommodated in such an extended Hilbert space. Thus the proton form-factor anomaly turned out to be an *experimental* fore-runner of the color hypothesis which was to be subsumed in a non-abelian gauge theory (QCD) that was taking shape, with color as the right candidate for the needed attribute [see Rajasekharan for details].

5.3 Hadron Spectroscopy With Quarks

The *uds*-flavoured quark structure of hadrons gave rise to a straightforward extension of the isospin group from $SU(2)$ to $SU(3)$ which, together with the spin group $SU(2)$, led to an $SU(6)$ extension of Wigner's $SU(4)$ group for nuclei. This was a most pleasing development for the classification of 2- and 3-quark hadrons in their ground states, while their excited configurations needed a further extension to $SU(6) \times O(3)$ to take care of internal orbital excitations. On the basis of this group, Dalitz [1966] made a detailed classification of possible hadron resonances, and most of the observed resonances fitted nicely with this pattern, except for a few odd ones which would presumably require more subtle dynamical considerations. Further checks were provided by their decay patterns, mostly to pions and nucleons, for which the principal mechanism is via single quark transitions [Becchi-Morpurgo 1965], in close parallel to nuclear e.m. transitions. The Becchi-Morpurgo mechanism proved extremely successful for explaining most two-body decays of hadron resonances, thus providing powerful checks on the (Dalitz-like) $SU(6) \times O(3)$ assignments on their expected energy levels on the basis of a simple harmonic oscillator model (Greenberg-Resnikoff 1966; Karl-Obryk 1968], except for certain anomalies which remained unexplained. One such anomaly was the observation of considerably enhanced

modes for heavy mesonic (η) decays compared with their pionic modes. This was explained by taking account of "Galilean invariance" of the single quark pion interaction [Mitra-Ross 1967], pending a full-fledged relativistic treatment later [Feynman et al 1971].

5.3.1 $N - N$ Interaction via Quark Exchanges

Among other approaches to hadronic interactions in terms of the quark model, considerable attention was devoted to the derivation of the $N - N$ interaction in terms of the (microscopic) qq and $q\bar{q}$ interactions, through a basically "folding" process. The input form of the latter, in turn, would often be coulombic in the high momentum limit, but also one that would incorporate color confinement in the low energy limit (a la Richardson 1977]. Prominent Indian workers who have used these techniques systematically, include C.S. Warke, R. Shankar, B. K. Jain, and Y.K. Gambhir. But practical obstacles in the way of relativistic formulations (an essential requirement for *light* quarks !) and mathematically satisfactory solutions of the relativistic two- and three- quark problems impeded further progress. A good perspective on such limited studies is offered by the Book of R.K. Bhaduri: Models of the Nucleon (Addison-Wesley. 1988).

5.4 Covariant Salpeter Eq : Markov-Yukawa Principle

In this respect, a major formulation was initiated by Feynman et al [1971], FKR for short, in a novel approach to hadron structure which insisted on inclusion of (low energy) spectroscopy on par with high energy processes in any serious quark level study of the strong interaction problem, with Lorentz and gauge invariance as integral parts of the underlying formalism. This was to prove a big incentive for more systematic studies of the few-quark systems (even 3 decades after QCD had been formally christened as a strong interaction candidate). This coveted project was taken up in the Eighties by the Delhi group (D. S. Kulshreshtha, A.N. Mitra, I.Santhanam, N. N. Singh] in a step by step manner, using the Bethe-Salpeter Equation (BSE) as the basic dynamics, but with the crucial recognition that the time-like degree of freedom must *not* be taken on par with the space-like d.o.f.s (this lesson was learnt from the difficulties of the FKR approach precisely in this regard). This led to a reappraisal of the Salpeter Equation (1952), based on the Instant Approximation to the BSE, thus giving it a 3D content. But the (remaining)

time-like information had to be recovered by *reconstructing* the 4D BS wave function in terms of 3D ingredients (This information was already there in the original Salpeter equation, but had apparently got lost in the subsequent literature), so as to give a two-tier structure : the (reduced) 3D BSE form attuned to hadron spectroscopy, and its (reconstructed) 4D form ideal for the calculation of various hadronic transition processes via Feynman diagrams for appropriate quark loops. On these lines an extensive study of hadron spectroscopy for $q\bar{q}$ and qqq systems, provided a unified view of both spectroscopy and transition processes within a single unified framework. Relativistic covariance was ensured by giving a special status to the c.m. frame of the concerned hadron (as quark composite). This 2-tier Salpeter-like framework, in turn, found a firm theoretical basis in a 50-year old principle, traceable to Markov (1940) and Yukawa (1950), which came to be known as the Markov-Yukawa Transversality Principle (*MYTP*). It not only provided a Lorentz-covariant meaning to this framework for a 3D-4D interlinkage of all Salpeter-like equations via *CovariantInstantaneity*, but also gave it a more secure foundation through a new *gaugeprinciple* in which the quark constituents interact in a direction *transverse* to the momentum P_μ of the composite hadron. This was already quite satisfactory for hadron spectroscopy (which needed a 3D equation only), but unfortunately gave rise to a ‘Lorentz mismatch disease ’ for Feynman diagrams involving 4D quark-loops, (since the different vertices involved different c.m. frames), leading to *complexities* in the resultant hadronic amplitudes ! To cure this disease needed a further strategy, involving Dirac’s light-front formalism, whose main ideas are outlined as follows :

5.5 Dirac’s Light-Front Dynamics and MYTP

Apart from laying the foundations of QFT through his famous Equation, Dirac made two great contributions within a year’s gap from each other: a) light-front dynamics (LFD)[1949]; b) constrained dynamics [1950]. The former which is the subject of this discussion, is characterized by the following idea: A relativistically invariant Hamiltonian can be based on different classes of initial surfaces: instant form ($x_0 = \text{const}$); light-front (LF) form ($x_0 + x_3 = 0$); hyperboloid form ($x^2 + a^2 < 0$). The structure of the theory is strongly dependent on these 3 surface forms. In particular, the ”LF form” stays invariant under 7 generators of the Poincare’ group, while the other two are invariant only under

6 of them. Thus the LF form has the maximum number (7) of "kinematical" generators (their representations are independent of the dynamics of the system), leaving only 3 "hamiltonians" for the dynamics.

Dirac's LF dynamics got a boost after Weinberg's discovery of the $P_z = \text{inf}$ frame which greatly simplified the structure of current algebra. The Bjorken scaling in deep inelastic scattering, supported by Feynman's parton picture, brought out the equivalence of LF dynamics with the $P_z = \text{inf}$ frame. The time ordering in LF-dynamics is in the variable $\tau = x_0 + x_3$, instead of $t = x_0$ in the instant form. Indeed, the LF dynamics often turns out to be simpler and more transparent than the instant form, while retaining the net physical content more efficiently. The LF language was developed systematically within the QFT framework through world-wide activity since the Seventies (Kogut, Susskind-1974). Indian participation was visible lately (Srivastava (1999), Mitra (1999)] .

5.5.1 Covariant Light Front Dynamics

The final link in the FKR programme was achieved by endowing the *MYTP* framework with a "covariant light-front" approach which yields loop integrals free from time-like momentum anomalies. This was checked from a recent application of *MYTP* in the LF formalism to the Pion Form Factor [Mitra, Phys Lett. B 1999]. The extension to the qqq problem also goes through, but is more technical [Mitra-Sodermark hep-ph/0104219].

5.5.2 Heavy Quarkonia and Exotic States

We end this section with some comments on the developments since the so-called "November revolution" (1974) which led to the discovery of Charmonium $c\bar{c}$, as the first example of "heavy quarkonia", to be followed (1977) by the discovery of a still heavier one ('Beauty' $b\bar{b}$), culminating in the identification of the 'Top' at the end of the last Century. This led to extensive activities in heavy quarkonia spectroscopy on both theoretical and experimental fronts. In these activities, Indian participation has also been (expectedly) widespread. Allied things like QCD exotic states like $q\bar{q}$ hybrids and gg glueballs, also received due attention. Such states are characterized by more than the minimum number of quarks compatible with their basic quantum numbers, yet permitted by the quark model in principle) which are hard to detect (!) A prominent Indian group led by Kamal

Seth participated in the heavy quarkonia programmes in Fermilab as well as the CLEO Collaboration for e^+e^- annihilation at Cornell. Among his successes were the detection of *two* rare radially excited pseudoscalar charmonium states.

5.5.3 Hidden Color

As a closely related item, "hidden colour" is a concept which arises from the colour confinement ideas in QCD and the quark model for the multi-quark configurations like 6-q, 9-q, 12-q etc. By the very nature of such configurations (say $3n$), they have a direct bearing on the corresponding nuclear configurations with numbers n , and it is of interest to ask if certain anomalies pertaining to the latter can be explained by this novel concept. In this respect, some notable Indian efforts deserve particular mention. Afsar Abbas at IOP Bhubaneswar made a systematic group theoretic study of the amount of hidden colour in 9-q and 12-q configurations (Phys Lett 167B ((1986) 150), and used this concept to explain the experimentally observed "hole" in the matter distribution in the nuclei: 4-He, 3-He and 3-H. Abbas has also found that the same concept is useful in explaining such diverse properties as that of the "neutron halo" , nuclear clusters and nuclear molecules (Mod Phys Lett A16 (2001) 735). If confirmed by further probes, it should warrant the interpretation that all these properties represent the signatures of the quark degrees of freedom in the ground state properties of nuclei. It is understood that experiments at KEK Japan and GANIL France are under way for testing these predictions.

6 Nuclear Astrophysics: QGP Transition

An important area of NP dates back to its astrophysical applications which were pioneered by Hans Bethe (1939) through his analysis of $p - p$ chain and carbon-nitrogen cycles for turning hydrogen into helium. Although in a dormant state for some decades, it has come to life once again for more than one reason. The study of neutrinos from the Sun has acquired a new dimension when the traditional mismatch of expected rates compared to the Davis result, has started getting resolved only recently after the latest Kamiokande results were put in perspective with the expectations from "neutrino mixing" ! A more important reason for the present tendency of nuclear physics to interface with

the cosmological domain has been triggered by the use of heavy ion beam reactions, so as to facilitate the transition to the "Quark-Gluon-Plasma" (QGP) state, and thus help create early universe conditions of high temperatures in the laboratory. Although this programme is still at an early stage, it has already brought together two hitherto disparate groups (nuclear and plasma physicists) towards a common goal of re-enacting a phase transition— that between the hadronic and the QGP phases—in the laboratory.

6.1 Matter at High ρ and T : QGP Transition ?

Closely related to the domain of Nuclear Astrophysics, is matter at high densities (ρ) and temperatures (T) which naturally exists in the stars, but the task of simulating such conditions in the laboratory represents a major challenge which has become a subject of intense interest during the last 2 decades, involving both theoretical and experimental activities in tandem. Now theoretical calculations based on temperature-dependent field theory (QCD) for high densities (incorporated through suitable chemical potentials) suggest that under conditions of high T, ρ in a volume large compared to a typical hadronic volume, a transition occurs to a new state of matter where quarks are no longer confined to their individual hadrons, but can move freely within the larger volume. This state which is called the quark-gluon-plasma (QGP) state, illustrates the intertwining of two hitherto distinct branches of physics— nuclear and plasma physics— brought about under conditions of high temperature. For illustration, we present a brief sketch of a sustained investigation by Subol Dasgupta (McGill) and his colleague George Bertsch in this regard.

6.2 Boltzmann-Uehling-Uhlenbeck Model

Dasgupta and Bertsch developed a transport model for heavy ion collisions at intermediate energies, termed the BUU (Boltzmann- Uehling-Uhlenbeck) model, which has been in use for the last two decades, and has the following essential elements. In a collision of one nucleus against another, in the lowest approximation, each nucleus can be regarded as a collection of "frozen" nucleons. Taking first a hard scattering model for simplicity, when the two nuclei pass through each other, one nucleon from a nucleus will scatter off another nucleon from the other nucleus provided the impact parameter between the two nucleons is less than $\sqrt{\sigma(s)/\pi}$, $\sigma(s)$ being the cross section for a 2-nucleon collision at c.m. energy

s. If the nuclei are moderately large, after a few collisions the nucleons will not remember which nucleus they came from ! One then finds the experimentally testable result that after a time of the order of $10^{-24}sec$, the ordered motion has changed, the collisions have ceased and nucleons are streaming freely.

In an alternative scenario, a nucleus by itself stays bound in a mean field (a la Hartree-Fock theory). Two such nuclei can be boosted towards each other. When they are passing through each other, any nucleon will feel the mean field of all other nucleons, not just the one they originally belonged to (S. Koonin). An advantage of this scenario is that it is not necessary to consider the nucleons as " frozen" before collisions (unlike the BUU model), and Fermi motion is easy to incorporate.

DB were able to combine both the scenarios by replacing Hartree-Fock by Vlasov propagation, thus facilitating the use of Vlasov equations which are familiar in electron plasma theory. The resulting model has been used to i) put narrow limits on the compressibility of nuclear matter from heavy ion data; and ii) predict production of particles like pions and photons. [G. F. Bertsch and S. Das Gupta, Physics Reports 160(1988)189]

6.3 Other Indian contributions

Among the more indigenous Indian contributions in this area, those by B. Banerjee, J. Parikh, L. Satpathy, C.P. Singh and B. Sinha are among the more prominent ones. Parikh's publications (including 3 books) reflect his simultaneous expertise in the dual fields of nuclear and plasma physics, wherein he has proposed a signature for testing formation of QCD plasma: look for pion correlations in relativistic heavy ion collisions. [This was a year earlier than the famous Matsui- Satz proposal on the J/PSI suppression].

Satpathy has successfully employed a diatomic-like molecular model (termed Dynamic Potential Model) in describing the phenomena of nuclear molecular resonances observed in heavy-ion collisions.

Singh, whose group is a member of the experimental PHENIX Collaboration at BNL, has made extensive studies of the signals of QGP in terms of his proposed equation of state, and found some unique signatures in the *strangeness* sector, which are being actively looked at by experimentalists probing QGP.

Sinha's notable contribution in relativistic heavy ion collisions lies in the recognition of

single photons and dileptons as signatures of QGP. which are being looked for at CERN.

6.4 Experiments at RHIC: Results from 4 Groups

To explore this state, experiments have been carried out successively at Bevalac (Berkeley), AGS (Brookhaven), SPS (CERN), and now at the new Relativistic Heavy Ion Collider (RHIC) at Brookhaven. Since the QGP phase transition is associated with quark *deconfinement*, the central issue is how to observe and interpret this feature unambiguously. So far, in the earlier colliders before RHIC, no clean signatures have been found, but the latest outcome from RHIC (which has an order of magnitude higher energy), is quite positive. This is indicated by the results from four groups analysing the data from two beams of gold ions clashing at several interaction zones around the ring shaped facility : 1) BRAHMS; 2) PHENIX; 3) PHOBOS; AND 4) STAR , all in Nucl Phys. **A 757**, (2005). Their consensus is that the fireball is a liquid of strongly interacting quarks and gluons, rather than a gas of weakly interacting ones. The liquid is dense, but seems to flow with very little viscosity, approximating an ideal fluid ! The RHIC findings were reported at the April 2005 APS meeting in Tampa.

7 Retrospect : More Maths For Nucl Physics

The foregoing is merely a bird's eye view of the phenomenal growth of Nuclear physics during the last 75 years, whose scope has shrunk further by the emphasis on Indian contributions where relevant in the Global context. This growth has necessarily involved a dovetailing of Nuclear physics with other major branches of physics, from particle physics to quark model QCD and all the way to early universe cosmology involving QGP transitions, bringing together their characteristic techniques. Thus the investigations of the QGP transition has involved an active interaction of Nuclear physics techniques with those of Plasma physics (Vlasov eqs). Similarly, the merging of traditional Nuclear physics items with those of Particle physics has brought to the fore the need for *relativistic* formulations with all their mathematical sophistications such as 4D covariance and a new "gauge principle" viz., the Markov-Yukawa Transversality Principle as a possible dynamical scenarios for a joint solution of the 2- and 3-quark problems.

Finally a few words (not covered in the text) on the extended scope of nuclear studies to include highly mathematical quantum techniques, especially the role of newer and newer methods of angular momentum as well as the techniques of Quantum Groups, for the solution of diverse problems in Nuclear physics. In this endeavour, Indian contributions have been quite prominent, especially those emanating from the MATSCIENCE group of V. Devanathan, R. Jagannathan and K. Srinivasa Rao, who have investigated such problems in a most comprehensive fashion, with an impressive list of publications.

In conclusion, it is fair to say significant Indian contributions in this area (as in most others !) have been of a theoretical nature, while experimental NP on Indian soil is still to get off the ground. On the other hand, Indian workers have generally shown a high degree of competence in working with bigger Western groups, a necessary condition for success in experimental NP.

I am grateful to several Indian colleagues in India and abroad, for readily responding to my request for bringing their work to my attention. Any omissions in this regard are entirely mine. I have also benefitted from the article of Henley and Schiffer in "More Things in Heaven and Earth" [B.Bederson Ed, APS 1999].